Performance-Based Specifications for Heavy-Duty Asphalt Mixes for Use in Southern Ontario

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Abstract

Typically, a homogeneous pavement design is employed when constructing a road section. However, segments such as the approach intersection in a road section are subject to more severe loading due to the presence of static, accelerating, and decelerating traffic compared to the rest of the road section. The increase in traffic loading has negatively impacted the service life of approach intersections with high truck traffic volume in York Region. To ensure adequate durability, a more resilient pavement design is required for these approach intersections. Field results and past studies have indicated that relying solely on a volumetric design approach may not provide a comprehensive understanding of the asphalt mix under heavy traffic loading. Thus, the use of performance-related specifications could be utilized to produce high-performing asphalt mixes, resulting in an increased service life and reduced lifecycle cost. To evaluate this hypothesis, six Stone Mastic Asphalt (SMA) mixes, comprising three performance grade (PG) asphalt binders (PG70-28, PG76-28, and PG82-28) and two nominal maximum aggregate sizes (NMAS) of 9.5mm and 12.5mm, were produced under controlled laboratory conditions. The Disk-Shaped Compact Tension (DC(T)) Test was performed to characterize the low-temperature cracking resistance of the asphalt mixes, while the Illinois Flexibility Index Test (I-FIT) was used to evaluate the intermediate temperature cracking resistance. The Hamburg Wheel Tracking Test (HWTT) was employed to assess the shear resistance of the asphalt mixes. The results were compared to a recent plant-produced asphalt mix (WMA SP12.5FC2-PG70-28) used in York Region. A preliminary performance-based specification was developed to evaluate heavy-duty asphalt mixes, and a life cycle cost analysis was performed to determine the potential benefits of using a heavy-duty asphalt mix as a surface course over the conventional asphalt mix used in York Region.

Introduction

According to the Transportation Association of Canada (TAC, 2013), the vast and diverse landscape of Canada presents challenging conditions for transporting 90% of goods and services by truck. Therefore, transportation agencies play a crucial role in designing roads that perform optimally during their service life while ensuring user safety and using cost-effective and environmentally sustainable pavement materials.

Although a standard pavement design is typically applied to an entire road segment, approach intersections, turning lanes, and bus stops face unique loading scenarios that make them more susceptible to pavement failure, such as rutting or permanent deformation (NCAT, 1998). These areas are affected by high shear stresses generated by vehicle movements, which require more frequent maintenance, leading to increased costs and time expenditure.

The increasing traffic volume, especially heavy trucks with high axle loads, and harsh environmental conditions pose significant challenges for transportation agencies in Southern Ontario, reducing pavement service life. Therefore, it is crucial to consider the impact of future population growth, which will increase traffic volume and loading, as well as the effects of climate change when designing pavement materials.

Asphalt Mix Design

Over the past 80 years, asphalt mix design has been developed to ensure desirable pavement properties throughout its service life, including the prevention of rutting and cracking. This involves determining optimal proportions of aggregate, asphalt binder, additives, and supplementary materials, as well as designing, producing, laying down, and compacting the mix to meet durability and stability requirements. Durability refers to the pavement's ability to maintain its structural integrity under climate and traffic loading, while stability refers to its resistance to permanent deformation (Bonaquist, 2014).

Various asphalt mix design methods have been developed worldwide, including recipe, empirical testing, analytical computations, volumetric method, performance-related testing, and fundamental testing (Francken, 1998). The Marshall mix design and the Superpave mix design are the two most widely adopted methods globally, with the latter being volumetric and the former empirical.

However, pavement distresses such as rutting and cracking have shown that the Superpave mix design approach may not accurately predict the asphalt mix's durability and resistance to rutting and cracking in the short- and long-term. Moreover, the current asphalt mix design methods used in North America may not adequately predict asphalt pavement performance in the field. The addition of components such as Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), warm-mix asphalt additives, rejuvenators, polymers, and fibers in asphalt mixes has further complicated the issue (NCHRP 9-57, 2016). Therefore, it is crucial to introduce testing that can assess an asphalt mix's durability and improve its resistance to rutting and cracking while increasing reliability (NCHRP 9-57, 2016).

Balanced-Mix Design

Balanced Mix Design (BMD) refers to an asphalt mix design approach that employs performance tests on appropriately conditioned specimens to assess multiple modes of distress, accounting for mix aging, traffic, climate, and pavement location (NCHRP, 2018). BMD involves conducting two or more performance tests, such as rutting and cracking tests, to evaluate the asphalt mixes' resistance to pavement distress. Figure 1 illustrates the three primary BMD methods currently used in some US states, including Texas, Illinois, Louisiana, and New Jersey (Bennert, 2018; Zhou, 2017; Cooper & Mohammad, 2018; Ozer & Al-Qadi, 2018; Newcomb & Zhou, 2018). These tests may be performed as part of: a) performance-verified volumetric design, b) performance-modified volumetric design, or c) performance design alone, targeting asphalt mix durability. In performance-verified volumetric design, performance tests are conducted to confirm the mix's resistance to a specific distress, such as rutting. In performance-modified volumetric design, performance tests are performed to adjust the mix proportions, such as increasing the asphalt content, to enhance its resistance to rutting. In the third method, volumetric properties are not mandatory, and the design relies solely on performance response (Newcomb & Zhou, 2018).

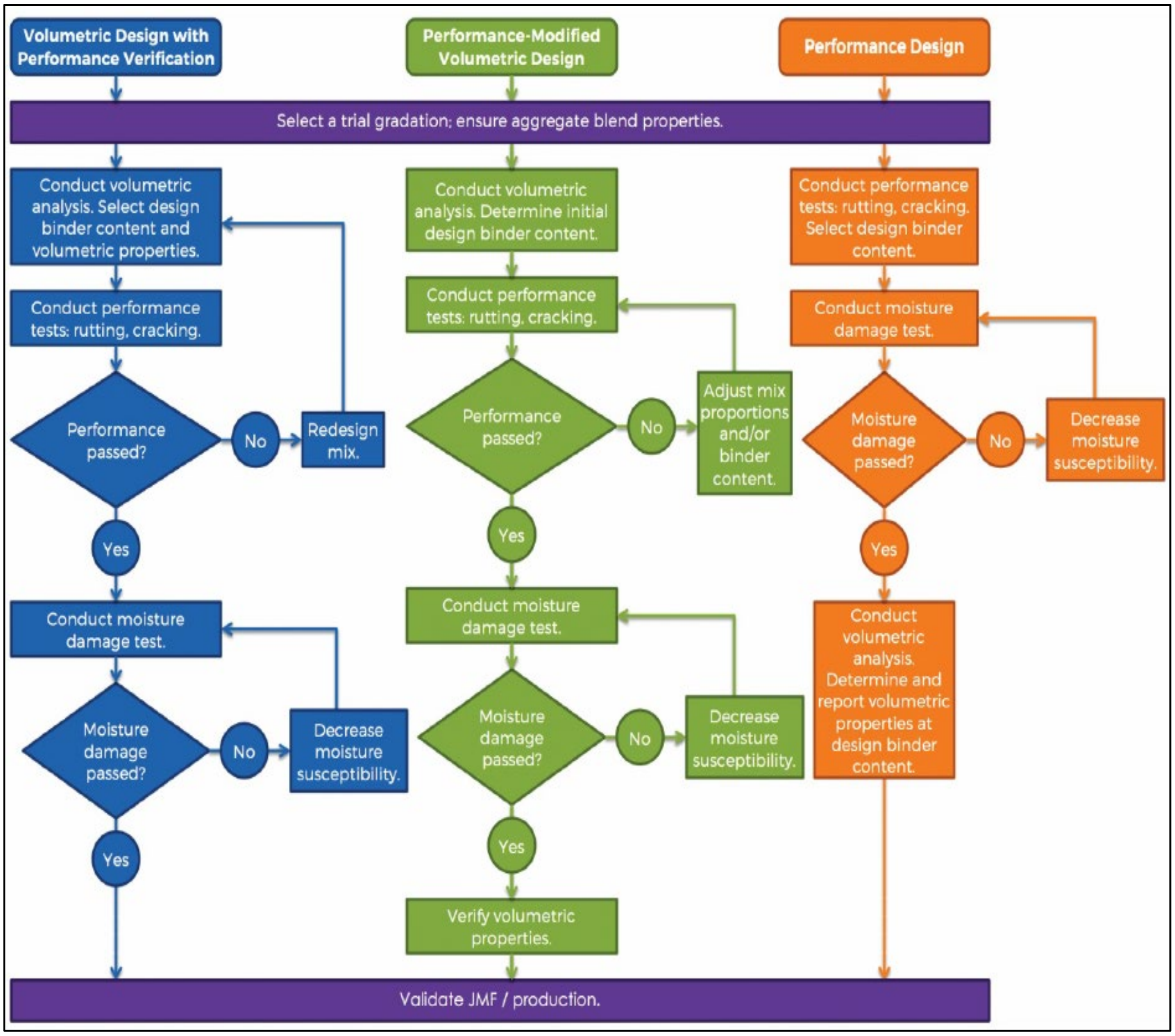


Figure 1: Schematic Illustration of Three BMD Approaches (NCHRP, 2016)

Case Study

The Regional Municipality of York (York Region), situated in the Greater Toronto Area, is a rapidly growing municipality and the third largest in Ontario and seventh largest in Canada. The region spans approximately 1,776 km^2 and is comprised of nine local municipalities, bounded by the City of Toronto to the south, the Region of Durham to the east, the Region of Peel to the west, and Simcoe County and Lake Simcoe to the north (Kafi Farashah et al., 2021). York Region is home to more than 1.2 million residents and 52,000 businesses across nine cities and towns, with a projected population growth to reach 1.8 million by 2051. While the majority of transportation assets in York Region are in good condition, aging infrastructure and population growth necessitate an investment of over $1.1 billion over the next two decades to maintain the region's roads infrastructure, according to the 2019 Transportation State of Infrastructure Report Card (Kafi Farashah et al., 2021).

Figure 2: York Region Location (Kafi Farashah et al., 2021)

Due to the increasing population and number of vehicles, including trucks, and changing temperature patterns, York Region is experiencing premature pavement failure in many of its heavy truck traffic intersections, mainly in the form of deformation or rutting (Kafi Farashah et al., 2021). To identify the cause of pavement premature failure, York Region selected six approach intersections for evaluation to assess their in-service performance and determine the need for material improvement. According to the findings from the field investigation, rutting damage was observed only in the asphalt surface layer, indicating that the pavement structures were structurally sound, and the rutting was likely caused by inadequate asphalt mix stability (Kafi Farashah et al., 2021). Additionally, the field results indicated that relying solely on volumetric design may not fully reflect the mix's performance under heavy traffic. Therefore, it is recommended to include performance testing in the design stage for a more comprehensive understanding of the mix's resistance to rutting and cracking and desired reliability.

The purpose of this study was to propose a sustainable asphalt surface mix for approach intersections in Southern Ontario that can withstand heavy truck traffic and resist rutting and cracking, through performance testing. To achieve this goal, six Stone Mastic Asphalt (SMA) mixes were developed with controlled laboratory conditions, consisting of three performance grade (PG) asphalt binders (PG70-28, PG76-28, and PG82-28) and two nominal maximum aggregate sizes (NMAS) of 9.5mm and 12.5mm. The performance of the asphalt mixes was evaluated using the Disk-Shaped Compact Tension (DC(T)) Test to measure low-temperature cracking resistance, the Illinois Flexibility Index Test (I-FIT) to evaluate intermediate temperature cracking resistance, and the Hamburg Wheel Tracking Test (HWTT) to assess shear resistance. The results were compared to a Warm Mix asphalt (WMA SP12.5FC2-PG70-28) recently used in York Region.

Lab-produced Asphalt Mixes

The study utilized aggregates from a single quarry to maintain consistency, and the asphalt binders were obtained from a single producer. Gabbro was the type of aggregate used in this research, which is included in the MTO's Designated Sources for Material (DSM) list. Table 1 provides information on the aggregate gradation, asphalt binder content, specific bulk gravity of aggregate, and volumetric properties (including VMA and VFA) of the laboratory-produced asphalt mix design. To simulate aging, the mixes underwent a 4-hour short-term aging process at 135ºC in an air-forced oven, following AASHTO R30 guidelines.

Table 1: Physical Properties of Lab-Produced Asphalt Surface Mixes

Property	**Sieve Size (mm)**	***OPSS 1151 Requirement for SMA 9.5***	**SMA 9.5 Aggregate Gradation (PG-70-28, PG-76-28, and PG-82-28)**	***OPSS 1151 Requirement for SMA 12.5***	**SMA 12.5 Aggregate Gradation (PG-70-28, PG-76-28, and PG-82-28**
Aggregate Gradation (% Passing)	25	*100*	100	*100*	100
	19	*100*	100	*100*	100
	12.5	*100*	100	*90-100*	93.1
	9.5	*70-95*	83.7	*50-80*	70.7
	6.7	-	46.2	-	44.6
	4.75	*30-50*	32	*20-35*	26.1
	2.36	*20-30*	22.1	*16-24*	18.4
	1.18	*max. 21*	17.6	-	15.4
	0.6	*max.18*	14.7	-	13.5
	0.3	*max.15*	12.6	-	12.2
	0.15	-	10.5	-	10.3
	0.075	*8-12*	8.6	*8-11*	8.7
Additive (Cellulose Fibre)		-	0.3% of Mix	-	0.3% of Mix
N_{des}		-	100	-	100
N_{ini}		-	8	-	8
N_{max}		-	160	-	160
Air Voids (%) at N_{des}		*4.0*	4.0	*4.0*	4.0
Voids in Mineral Aggregate, VMA (% minimum)		*17.0*	17.9	*17.0*	17.6

Property	*OPSS 1151 Requirement for SMA 9.5*	**SMA 9.5 Aggregate Gradation (PG-70-28, PG-76-28, and PG-82-28)**	*OPSS 1151 Requirement for SMA 12.5*	**SMA 12.5 Aggregate Gradation (PG-70-28, PG-76-28, and PG-82-28**
Asphalt Binder Performance Grade	-	PG-70-28, PG-76-28 and PG-82-28	-	PG-70-28, PG-76-28, and PG-82-28
Voids Filled with Asphalt, VFA (%)	-	77.9	-	78.3
Bulk Specific Gravity (G_{mb})	-	2.892	-	2.924
Dust Proportion, DP	-	1.5	-	1.6
Tensile Strength Ratio, TSR (%)	*70*	PG70-28 = 91.9 PG-76-28 = 93.1 PG-82-28 = 95.2	*70*	PG-70-28 = 83.5 PG-76-28= 85.1 PG-82-28 = 87.3
Asphalt Cement Content (%)	-	5.7	-	5.7
Voids in Coarse Aggregate, VCA_{mix}	$<VCA_{DRC}$	38.5<42.1	$<VCA_{DRC}$	38.9<42.6
Drain Down (%)	*Max 0.3*	0.1	*Max 0.3*	0.1

Notes: OPSS is Ontario Provincial Standard Specification, N_{des}, N_{ini}, N_{max} are number of gyrations at different compaction levels (design, initial, and maximum), G_{mb} is bulk specific gravity, and VCA_{DRC} is voids in coarse aggregate in Dry-Rodded condition.

Performance Tests for Evaluating Asphalt Mixes

The resistance of the asphalt mixes to rutting and cracking was evaluated through the consideration of the following performance tests.

Hamburg Wheel Tracking Test (AASHTO T324)

The asphalt mixes' resistance to rutting was evaluated using the Hamburg Wheel Tracking Test (HWTT), as presented in Figure 3. This test, following AASHTO T324, tracked a 158-lb (705-N) load steel wheel across the surface of a gyratory-compacted specimen (150mm in diameter and 62mm high) in a hot water bath maintained at 50°C. It assessed the asphalt mixes' performance under high in-service temperatures and in the presence of moisture, enabling the evaluation of moisture sensitivity in compacted asphalt mixes (Brown et al., 2009). In this study, the Hamburg Wheel Tracking test was conducted at additional temperatures of 44ºC and 58ºC to determine the effect of temperature on rutting resistance and moisture damage of the asphalt mixes. The rutting susceptibility of the asphalt mixes was measured using Low Voltage Displacement Transducers (LVDTs), which determined the accumulated permanent deformation. Figure 3 displayed a typical specimen before and after testing. Furthermore, the moisture susceptibility was determined by calculating the Stripping Inflection Point (SIP), which represented the intersection of the slopes of stripping and rutting. SIP, reported as the number of passes where a sudden increase in rut depth occurred, was used to assess the mix's overall behavior with respect to moisture damage (NCHRP, 2011). Figure 4 illustrated SIP and its relationship with moisture damage susceptibility.

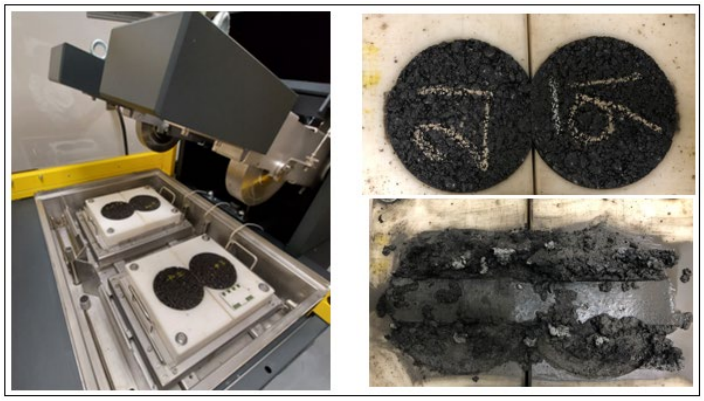


Figure 3: Hamburg Wheel Track Device Setup (left) and Test Specimens Before and After (Right)

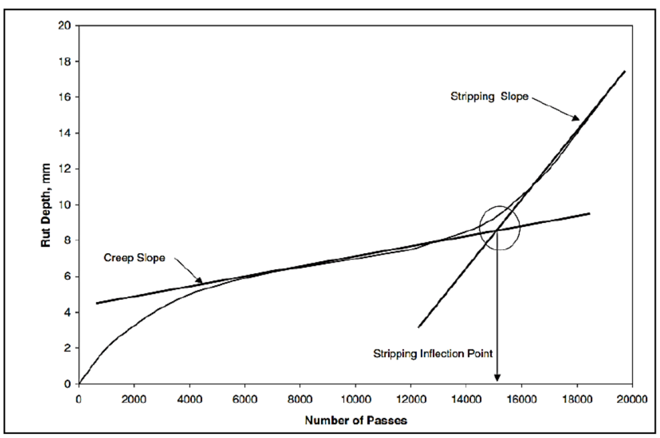


Figure 4: Typical Results from Hamburg Wheel Tracking Test (NCHRP, 2011)

Illinois Flexibility Index Test (I-FIT) Test (AASHTO TP124)

The I-FIT test is a method utilized for assessing the intermediate temperature cracking resistance of asphalt mixes. The test is conducted following the guidelines specified in AASHTO TP124. A 150 mm diameter and 180 mm height specimen, which has been compacted using the Superpave Gyratory Compactor (SGC), is cut into two 50 mm height discs. These discs are further divided into two replicates by cutting them with a tile saw. A notch measuring 15±0.5 mm in length and 1.5±0.5 mm in width is made at the center of the flat side of each half-disc, as illustrated in Figure 5. The samples are conditioned for 2 hours ± 10 minutes at 25±0.5ºC before testing, in an environmental chamber or water bath. The specimens are positioned on their flat side on two roller supports of the testing frame and tested at 25ºC, as shown in Figure 6. During the test, a monotonic load is applied by the machine at a rate of 50 mm/min until a crack initiates at the tip of the notch and propagates upwards. The test ends when the post-peak load reaches 0.1 kN. The test provides fracture energy, post-peak load slope, strength, and the flexibility index (FI) as parameters. FI is an empirical index that can be calculated using Equation 1.

$$\text{FI} = \frac{Gf}{|\text{m}|}\,(0.01) \tag{1}$$

Where:

FI = Flexibility Index
G_f = work of fracture, calculated as the area under the load-displacement curve (J/m^2) by dividing W_f (work of fracture) by the ligament area.
m = slope of post-peak softening curve

a) Asphalt disc specimen b) Cutting discs in half c) Cutting the notch

Figure 5: Specimen Preparation for I-FIT Test

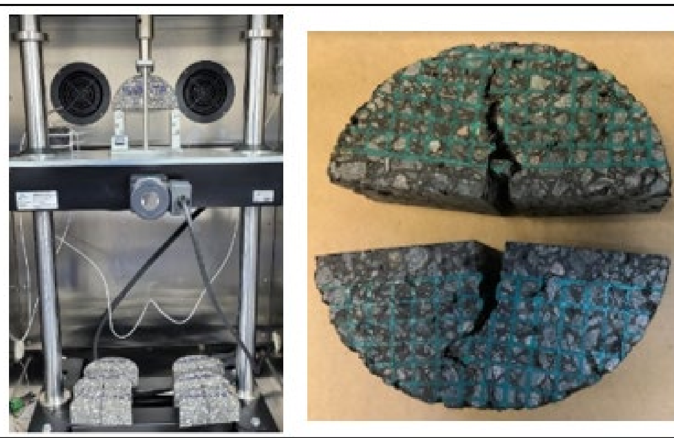


Figure 6: I-FIT Test Loading Fixture (Left) After Test (Right)

Disk-Shaped Compact Tension DC(T)Test (ASTM D7313)

The DC(T) test is utilized to assess the fracture characteristics of asphalt mixes at low temperatures following the guidelines specified in ASTM D7313. The dimensions of the specimens must comply with the following requirements: diameter of 150 ± 10 mm, thickness of 50 ± 5 mm, notch depth of 62 ± 3 mm, and notch width of 1.5 ± 0.5 mm. The specimens are conditioned for 8-16 hours in a freezer at a temperature that is 10 ºC higher than the low temperature grade of the PG asphalt binder employed in the asphalt mix. During the test, depicted in Figure 7, the specimen is subjected to a Crack Mouth Opening Displacement (CMOD) controlled mode and is pulled apart from the loading holes at a displacement rate of 1 mm/min. The test is terminated when a crack has propagated to the point where the post-peak load level has been reduced to 0.1 kN. The fracture energy (G_f) (J/m^2) is calculated by determining the area under the Load-CMOD displacement curve, which is then normalized by the product of the ligament length and thickness (fractured area) of the specimen, as shown in Equation 2. A higher value of Gf indicates that the asphalt mix is more resistant to low-temperature cracking.

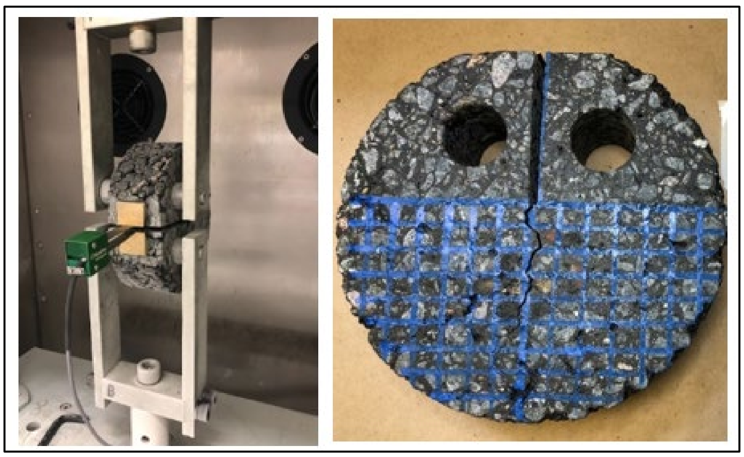


Figure 7: DC(T) Test Loading Fixture (Left) After Test (Right)

$$G_f = \frac{\text{Area}}{\text{B.L}} \qquad (2)$$

Where:

G_f = Fracture energy in J/m^2,
Area = Area under the load–CMODFIT curve until the terminal load of 0.1 kN is reached,
B = Specimen thickness in m, 0.050 m
L = Ligament length, usually around 0.083 m.

Asphalt Mix Characterization Results

Hamburg Wheel Tracking Test Results

In accordance with AASHTO T324, the HWTT was conducted on lab-produced asphalt mixes to assess their rutting resistance and moisture susceptibility. Typically, the test involves submerging specimens in water at 50°C until they reach a total rut depth of 12.5mm or undergo 20,000 passes, whichever comes first. However, this study chose a tolerable total rut depth of 6mm for safety reasons. This trigger level aligns with the recommendation of ASTM 1989, which states that a rut depth below 6mm does not require pavement treatment (ASTM, 1989).The number of passes was also increased to 40,000 to investigate each mix's behavior under harsh conditions and identify high-rut resistant asphalt mixes. To assess the sensitivity of the asphalt mixes to temperature, the HWTT was conducted at 44°C, 50°C, and 58°C. he testing temperature of 58°C was selected as it represents the Southern Ontario's climatic high PG temperature. Also, the testing temperature of 44°C was chosen based on the research conducted by the Ministry of Transportation Ontario (MTO) recommendation (Salehi-Ashani, 2019; Bashir et al., 2020).

Figure 8 displays the results of the HWTT for the six asphalt mixes produced in the lab, at testing temperatures of 44°C, 50°C, and 58°C. The data reveals that all asphalt mixes demonstrated remarkable resistance to rutting at a testing temperature of 44°C, as none of them exceeded the maximum rut depth of 6mm even after 40,000 wheel-track passes. This suggests that 44°C may not be an adequate testing temperature for differentiating between heavy-duty asphalt mixes. The study also found that asphalt mixes with greater NMAS and higher PG asphalt binder exhibited better resistance to rutting. For instance, SMA9.5-PG76-28 demonstrated a total rut depth of 2.92mm, while SMA12.5-PG76-28 had a lower total rut depth of 2.36mm at a testing temperature of 44°C. Additionally, Figure 8 demonstrates that at a testing temperature of 50°C and 40,000 wheel-track passes, all asphalt mixes except SMA9.5-PG70-28 exhibited remarkable resistance to rutting. SMA9.5-PG70-28 achieved a total rut depth of 6mm at 33,500 passes. The findings indicate that the SMA mixes with higher NMAS and PG asphalt binder offer better resistance to rutting at 50°C. Moreover, the study suggests that 50°C is insufficient to differentiate high rut-resistant asphalt mixes. According to Figure 8, only two asphalt mixes, SMA12.5-PG76-28 and SMA12.5-PG82-28, exhibited sufficient resistance to rutting (maximum rut depth of 6mm) after 40,000 wheel-track passes. Among the other mixes, SMA9.5-PG70-28 had the highest total rut depth of 22mm, followed by SMA12.5-PG70-28 with 9.61mm, SMA9.5-PG76-28 with 9.40mm, and SMA9.5-PG82-28 with 7.45mm. These results suggest that the 58°C testing temperature was effective in distinguishing asphalt mixes with high resistance to rutting.

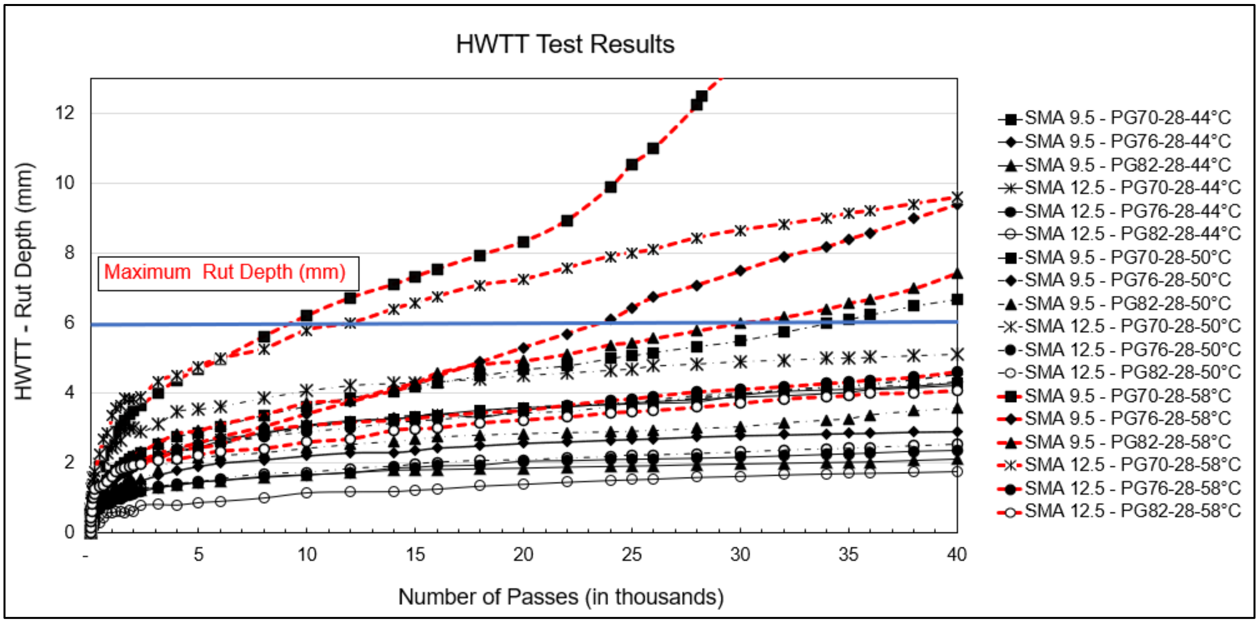


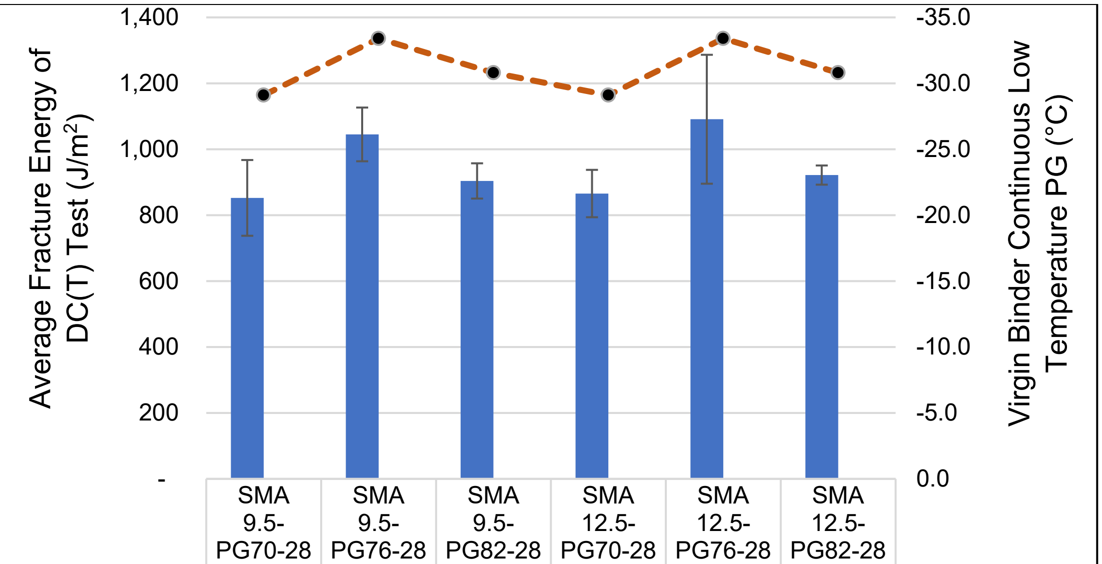
Figure 8: HWTT Test Results

Disk-Shaped Compact Tension DC(T)Test

The fracture behavior of asphalt mixes at low temperatures was characterized using the DC(T) test, conducted in triplets according to ASTM D7313 standards. The testing temperatures ranged from -18°C to simulate the lowest pavement surface temperature of -28°C. Figure 9 illustrates the results of the DC(T) test on the asphalt mixes, which show the average fracture energy, one standard deviation error bar, the Coefficient of Variation (COV), and the continuous low temperature grade of the virgin binder used in each mix.

The results showed that the SMA mixes with PG76-28 asphalt binder had higher DC(T) fracture energy than those with the same NMAS. This could be due to the fact that the virgin PG76-28 asphalt binder had the lowest continuous low-temperature grade of -33.4ºC, which is significantly below its corresponding low temperature PG of -28ºC. Conversely, the continuous low-temperature grades of PG82-28 and PG70-28 were -30.8ºC and -29.1ºC, respectively.

Furthermore, SMA mixes with 12.5mm NMAS provided slightly higher average DC(T) fracture energy compared to SMA mixes with 9.5mm NMAS. SMA12.5-PG76-28 provided the highest average DC(T) fracture energy of 1,091 J/m^2, followed by SMA9.5-PG76-28 with 1,045 J/m^2. Additionally, the average DC(T) fracture energy for all six tested lab-produced asphalt mixes was found to be 958 J/m^2. Therefore, the threshold value of 900 J/m^2 for DC(T) fracture energy was selected when evaluating heavy-duty asphalt mixes. The COV values for the DC(T) fracture energy of the six tested asphalt mixes varied from 3.2% to 17.9%, indicating low to medium variability in the results of the DC(T) test.



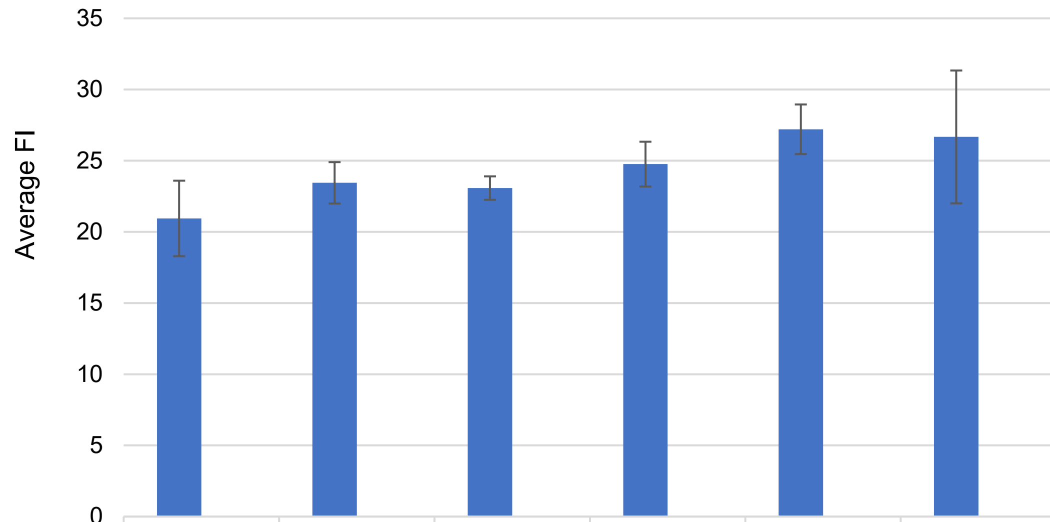
	SMA 9.5-PG70-28	SMA 9.5-PG76-28	SMA 9.5-PG82-28	SMA 12.5-PG70-28	SMA 12.5-PG76-28	SMA 12.5-PG82-28
Average Fracture Energy @-18°C	852	1,045	904	866	1,091	922
COV(%)	13.5	7.8	5.9	8.3	17.9	3.2
Virgin Binder Continious Low Temperature PG (°C)	-29.1	-33.4	-30.8	-29.1	-33.4	-30.8

Figure 9: DC(T) Fracture Energy Results at -18°C Testing Temperatures

Illinois Flexibility Index Test (I-FIT)

The intermediate temperature cracking resistance of the asphalt mixes was evaluated using the Flexibility Index (FI) in the I-FIT test, which was conducted on three replicates at 25°C following the AASHTO TP124 protocol.

Figure 10 displays the FI results for the SMA mixes with the same NMAS. The SMA12.5-PG76-28 mix exhibited the highest intermediate temperature cracking resistance, with an average FI value of 27.2, followed by SMA12.5-PG82-28 (FI=26.7) and SMA12.5-PG70-28 (FI=24.8). Meanwhile, the SMA9.5-PG70-28 mix displayed the lowest intermediate temperature cracking resistance, with an average FI value of 20.9. Therefore, a minimum FI value of 20 was established as the acceptable threshold for evaluating heavy-duty asphalt mixes. The COV for the Flexibility Index (FI) values of the six asphalt mixes ranged from 3.6% to 17.5%, indicating low to medium variability in the results of the I-FIT test. Furthermore, the results demonstrated that the SMA mixes with 12.5 NMAS tended to exhibit higher FI values than those with 9.5 NMAS and the same PG binder.



	SMA 9.5 - PG70-28	SMA 9.5 - PG76-28	SMA 9.5 - PG82-28	SMA 12.5 - PG70-28	SMA 12.5 - PG76-28	SMA 12.5 - PG82-28
Average FI @ 25°C	20.9	23.4	23.1	24.8	27.2	26.7
COV (%)	12.7	6.2	3.6	6.3	6.4	17.5

Figure 10: Flexibility Index Results at 25°C Testing Temperatures

Interaction Plots Between HWTT Rut Depth, DC(T) Facture Energy, and FI

To produce asphalt mixes with optimal performance, it is crucial to establish performance-related specifications for the three main criteria, namely low- and intermediate-temperature cracking resistance and shear resistance. Stiff mixes generally perform better in rutting resistance, whereas softer mixes are better at withstanding low- and intermediate-temperature cracking. Developing performance criteria is vital for understanding the durability of each asphalt mix and ensuring that high-performing asphalt mixes are produced. To gain a better understanding of the cracking and rutting resistance of the six lab-produced asphalt mixes, performance space diagrams were created to plot the HWTT rut depth at 58ºC after 40,000 passes against the DC(T) fracture energy and FI. These diagrams helped to characterize the cracking and rutting resistance of the different mixes. Preliminary thresholds for cracking and shear resistance of high-performance asphalt mixes for use in Southern Ontario's approach intersections were used to divide the performance space diagrams into four individual quadrants. Only the top left quadrant was considered to pass, indicating that the mix had high resistance to both rutting and cracking. The other quadrants were considered to fail as they did not meet the minimum trigger level for either cracking or rutting or both.

Figures 11 and 12 illustrate performance space diagrams showing the relationship between DC(T) fracture energy and rut depth, and FI and rut depth, respectively.

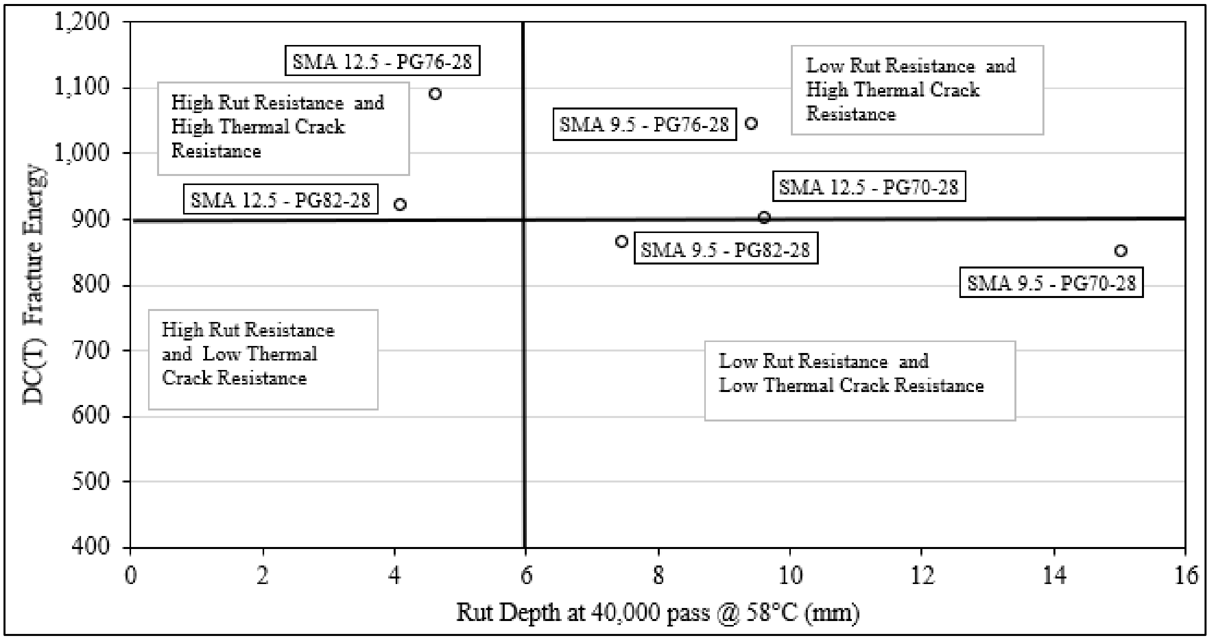


Figure 11: Performance Space Diagram of DC(T) Fracture Energy vs. Rut Depth with Preliminary Threshold Criteria

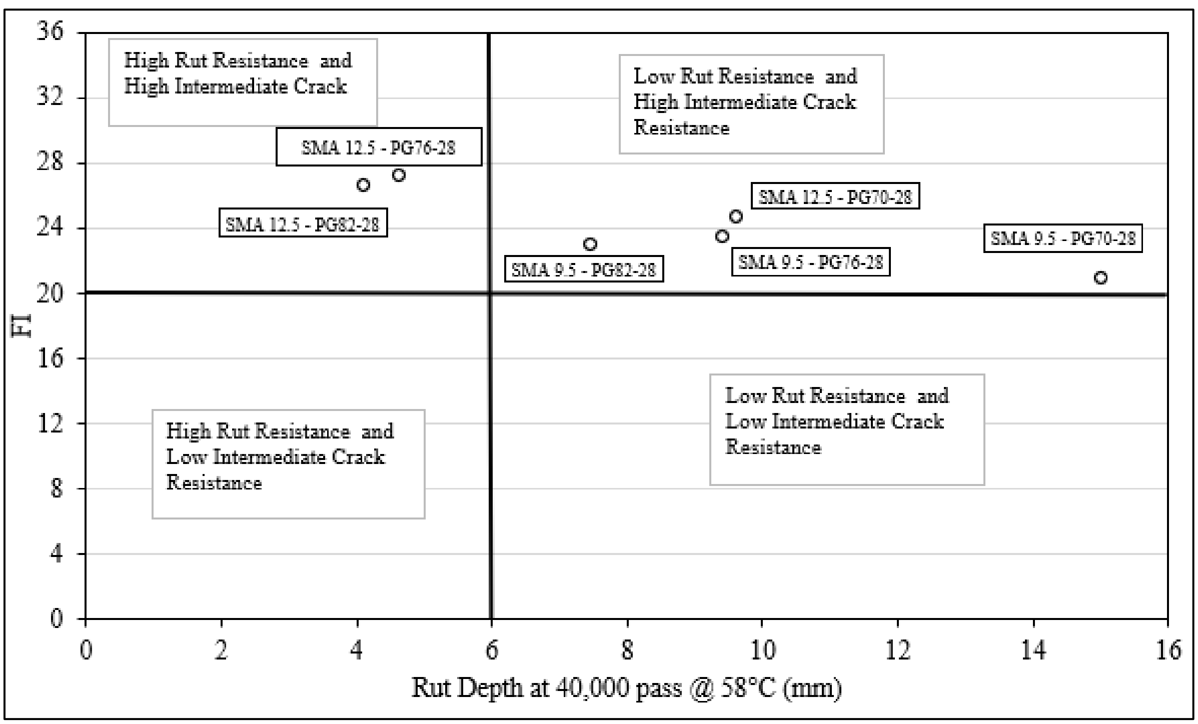


Figure 12: Performance Space Diagram of FI vs. Rut Depth with Preliminary Threshold Criteria

In terms of the performance space diagrams, SMA12.5-PG76-28 and SMA12.5-PG82-28 asphalt mixes performed well, exhibiting high resistance to rutting and good resistance to low and intermediate cracking, as illustrated in Figures 11 and 12. This indicates that these mixes possess desirable characteristics for high-performing asphalt mixes. However, considering the cost of PG76-28, which is lower than PG82-28, SMA12.5-PG76-28 was selected as the optimal asphalt mix. These findings suggest that performance space diagrams can be an effective tool in the asphalt mix design process for achieving a balanced mix that is resistant to both cracking and rutting, based on laboratory performance tests.

Life Cycle Cost Analysis

The objective of the life cycle cost assessment was to determine the financial requirements of constructing and maintaining an asphalt pavement at an approach intersection over its service life, while meeting the specified minimum acceptable level, using the SMA12.5-PG76-28 surface course asphalt mix. A comparison was made between the currently specified asphalt surface mix (WMA SP12.5 FC2-PG70-28) used in York Region and the proposed asphalt surface mix (SMA12.5-PG76-28) to assess the potential benefits of using the proposed mix. Before conducting the life cycle assessment, four steps were taken. Firstly, the benefits of using SMA12.5-PG76-28 were evaluated by comparing the results of the DC(T) fracture energy, I-FIT, and HWTT (at 58°C testing temperature) tests of the two asphalt mixes. Secondly, the benefits determined in the first step were applied to the current asphalt pavement deterioration curve used for high-traffic volume urban roads in York Region. Thirdly, appropriate pavement treatments and timing were selected to extend the average service life of the approach intersection to 50 years, matching York Region's roads asset management plan. Lastly, the Net Present Worth (NPW) method was used to calculate the life cycle cost.

Table 2 displays the results of the performance tests conducted on the SMA12.5-PG76-28 and SP12.5 FC2-PG70-28 asphalt mixes, including fracture energy, FI, and the number of passes required to reach 6mm deformation during the HWTT at 58°C. It should be noted that for SMA12.5-PG76-28, the rutting depth was assumed to reach 6mm after 40,000 passes as no data was available beyond this point. The data in Table 2 shows that using SMA12.5-PG76-28 asphalt mix for approach intersection applications results in improved low and intermediate temperature cracking resistance as well as rutting resistance, compared to the currently specified asphalt mix (SP12.5 FC2-PG70-28). Moreover, the table reveals that the highest importance factor (0.5) was assigned to rutting resistance due to its significance in terms of safety concerns at approach intersections. Intermediate temperature cracking resistance received a factor of 0.3, while low-temperature cracking resistance received a factor of 0.2. Overall, the SMA12.5-PG76-28 asphalt mix demonstrated a 171% improvement in performance compared to SP12.5 FC2-PG70-28.

Table 2: Performance Comparison SMA12.5-PG76-28 vs. SP12.5FC2-PG70-28

Testing Parameters	Asphalt Mixes: SMA12.5-PG76-28 (A)	Asphalt Mixes: SP12.5-PG70-28 (B)	Performance Improvement (%) C=(A-B/B)*100	Importance Factor (D)	Weighted Performance Improvement (%) (E = C x D)	Sum of Weighted Performance Improvement (%)
(HWTT) Number of Passes reached 6mm Deformation @ 58°C	40,000	11,500	248	0.5	124	171
FI @ 25°C	27.2	12	127	0.3	38	
DC(T) Fracture Energy @ -18°C	1,091	740	47	0.2	9	

York Region uses a comprehensive pavement condition assessment survey to evaluate the state of its road segments. The survey data is then analyzed to generate an overall Pavement Condition Index (PCI) that ranges from 0 to 100. A PCI score of 100 represents a newly constructed or rehabilitated pavement, whereas a score of 0 signifies the poorest or failed condition.

Figure 13 illustrates the estimated deterioration curve of asphalt pavement used by York Region for high-traffic volume roads with a strong subbase and a medium total asphalt layer thickness. Additionally, the estimated deterioration curve for SMA12.5-PG76-28 was developed, taking into account the 171% improvement in performance. Moreover, a minimum acceptable level of PCI value of 50 was used, indicating that the SP12.5FC2-PG70-28 and SMA12.5-PG76-28 mixes would reach the trigger level at 21 and 36 years of age, respectively. Table 3 provides an overview of the typical pavement life cycle activities, including preservation and rehabilitation measures, utilized by York Region to extend the life of high-traffic volume roads to 50 years.

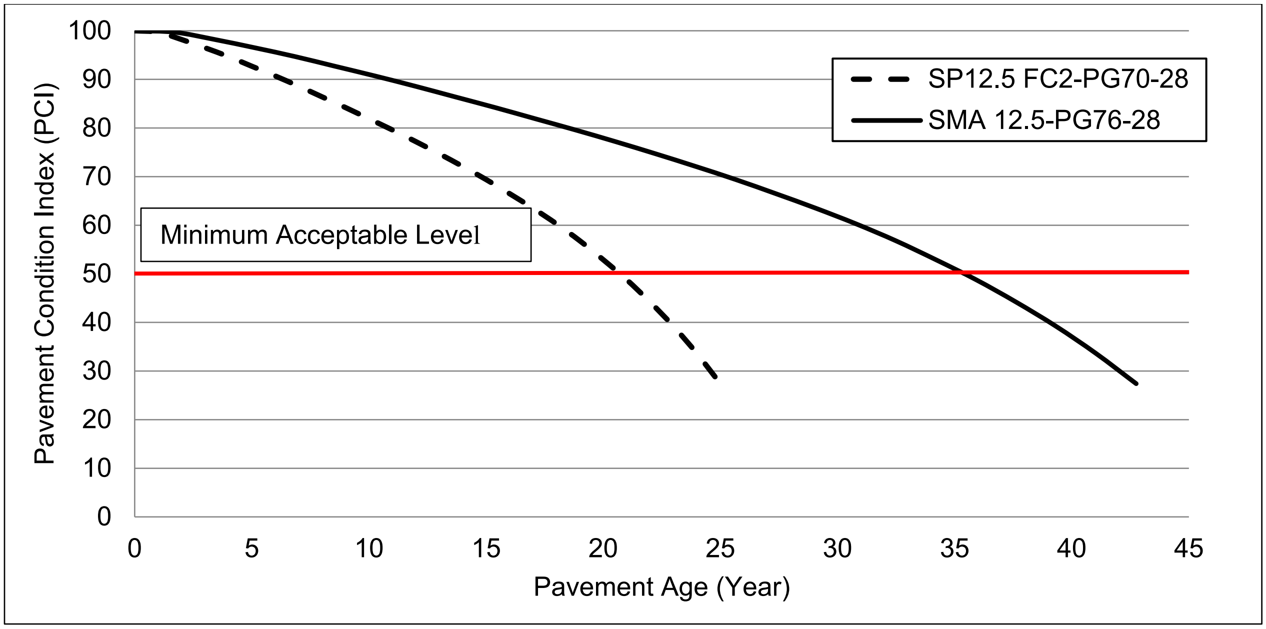


Figure 13: Deterioration Curves for SP12.5 FC2-PG70-28 and SMA 12.5-PG76-28 Asphalt Mixes with No Life Cycle Treatment

Table 3: Typical Life Cycle Activities for Heavy Traffic Volume Roads in York Region

Pavement Age (Year)	Life Cycle Activities
0	Initial Construction
4	Crack Seal (20%)
8	Surface Treatment
12	Crack Seal (20%)
17	Mill and Pave 50mm (100%)
21	Crack Seal (20%)
25	Crack Seal (20%)
30	Pavement Rehabilitation
34	Crack Seal (20%)
40	Surface Treatment
44	Crack Seal (20%)
48	Grind and Patch (20%)

Figures 14 and 15 depict the 50-year life cycle asphalt performance deterioration curves for the SP12.5 FC2-PG-70-28 and SMA 12.5-PG76-28 asphalt mixes, respectively. This information was derived from Figure 13 and Table 3, which provided the estimated asphalt pavement deterioration curves and typical life cycle activities used in York Region for heavy traffic volume roads.

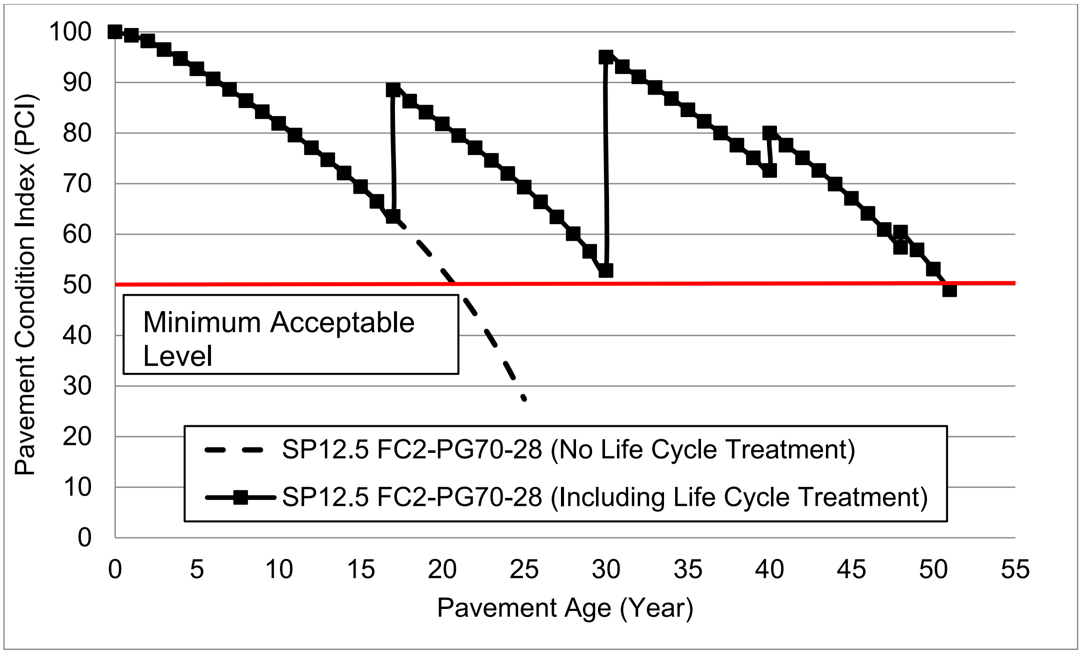


Figure 14: Deterioration Curves for SP12.5 FC2-PG70-28 Asphalt Mix (No Life Cycle Treatment vs. Including Life Cycle Treatment)

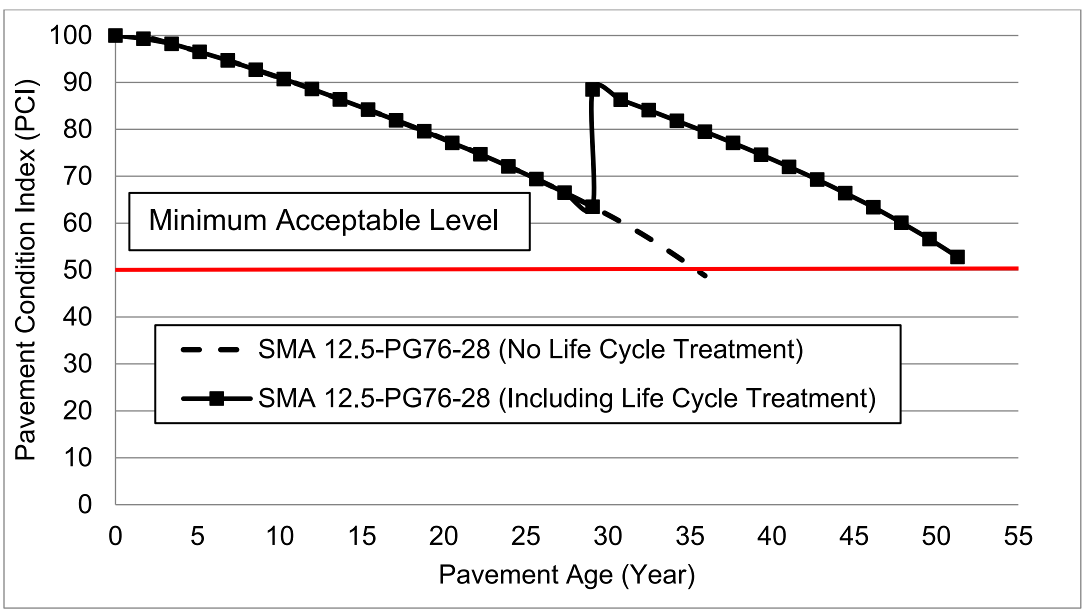


Figure15: Deterioration Curves for SMA 12.5-PG76-28 Asphalt Mix (No Life Cycle Treatment vs. Including Life Cycle Treatment)

The life cycle cost for the SP12.5 FC2-PG70-28 and SMA 12.5-PG76-28 asphalt mixes over a 50-year period was determined using the Net Present Worth (NPW) method, as shown in Equation 3. The costs were compared at discount rates of 0%, 2%, and 4%. It is worth mentioning that all costs are expressed per 1-lane.km (3,500m^2), and the initial construction cost unit rate is the average cost of building 4-lane roads in an urban environment.

$$NPW = IC + \sum_{j=1}^{k} (M\&R_j \times \left(\frac{1}{1 + i_{Discount}}\right)^{n_j}) \quad (3)$$

Where:

NPW = Net Present Worth ($),
IC = Initial Cost ($),
K = Number of future maintenance, preservation, and rehabilitation
$M\&R_j$ = Cost of j^{th} future maintenance, preservation and rehabilitation activity ($)
$i_{Discount}$ = Discount Rate,
n_j = Number of years from presents of the j^{th} future maintenance, preservation and rehabilitation activity

Tables 4 and 5 demonstrate the Net Present Worth (NPW) values calculated for maintaining roads built with SMA 12.5-PG76-28 and SP12.5 FC2-PG-70-28 asphalt mix surface course over a 50-year lifespan, considering various discount rate values. The findings indicate that although the initial construction cost of a 1-lane.km road with SMA 12.5-PG76-28 surface course was $105,000 higher, the overall 50-year life cycle cost was $218,400 lower at a 0% discount rate. Furthermore, the difference decreased to $72,975 and $3,391 at 2% and 4% discount rates, respectively. This suggests that at higher discount rates, the difference is not significant, and both alternatives have very similar costs. Furthermore, the results indicate that the number of life cycle activities required to maintain a road built with SMA 12.5-PG76-28 was lower than that of SP12.5-PG70-28, potentially resulting in reduced material production and hauling, lower fuel usage, and decreased greenhouse gas emissions.

Table 4: Life Cycle Net Present Worth for Maintaining Heavy Traffic Roads with SMA 12.5-PG76-28 Asphalt Mix Surface Course

Year	Life Cycle Activities	Unit	Unit Cost ($/m²)	Cost Per Lane.km (lane.km = 3,500m²)	0% Discount Rate	2% Discount Rate	4% Discount Rate
0	Initial Construction	m²	290	$ 1,015,000	$1,015,000	$1,015,000	$1,015,000
7	Crack Seal (20%)	m²	0.2	$700	$700	$609	$532
14	Surface Treatment	m²	15	$52,500	$52,500	$39,788	$30,317
21	Crack Seal (20%)	m²	0.2	$700	$700	$462	$307
29	Mill and Pave 50mm (100%)	m²	65	$227,500	$227,500	$128,108	$72,948
36	Crack Seal (20%)	m²	0.2	$700	$700	$343	$171
43	Crack Seal (20%)	m²	0.2	$700	$700	$299	$130
Total 50-Year Life Cycle Cost ($)				*$1,297,800*	*$1,297,800*	*$1,184,610*	*$1,119,405*
Average Cost ($)/Year				*$25,956*	*$25,956*	*$23,692*	*$ 22,388*

Table 5: Life Cycle Net Present Worth for Maintaining Heavy Traffic Roads with SP12.5 FC2-PG70-28 Asphalt Mix Surface Course

Year	Life Cycle Activities	Unit	Unit Cost ($/m²)	Cost Per Lane.km (lane.km = 3,500m²)	0% Discount Rate	2% Discount Rate	4% Discount Rate
0	Initial Construction	m²	260	$910,000	$910,000	$910,000	$910,000
4	Crack Seal (20%)	m²	0.2	$700	$700	$647	$598
8	Surface Treatment	m²	15	$52,500	$52,500	$44,808	$38,361
12	Crack Seal (20%)	m²	0.2	$700	$700	$552	$437
17	Mill and Pave 50mm (100%)	m²	36	$126,000	$126,000	$89,984	$64,685
21	Crack Seal (20%)	m²	0.2	$700	$700	$462	$307
25	Crack Seal (20%)	m²	0.2	$700	$700	$427	$263
30	Pavement Rehabilitation	m²	74	$259,000	$259,000	$142,986	$79,855
34	Crack Seal (20%)	m²	0.2	$700	$700	$357	$184
40	Surface Treatment	m²	15	$52,500	$52,500	$23,777	$10,935
44	Crack Seal (20%)	m²	0.2	$700	$700	$293	$125
48	Grind and Patch (20%)	m²	32	$112,000	$112,000	$43,292	$17,046
Total 50-Year Life Cycle Cost ($)				*$1,516,200*	*$1,516,200*	*$1,257,585*	*$1,122,796*
Average Cost ($)/Year				*$30,324*	*$30,324*	*$25,152*	*$22,456*

Conclusions

In order to establish performance specifications for assessing the resistance of asphalt surface mixes to rutting and cracking at high truck volume approach intersections in Southern Ontario, six proposed heavy-duty asphalt mixes were evaluated using the HWTT, I-FIT, and DC(T) tests. The study recommended that the HWTT test should be conducted at a temperature of 58°C with 40,000 wheel-track passes and that the rut depth acceptance threshold be reduced to 6mm from 12.5mm to address safety concerns. The data showed that a pre-determined DC(T) fracture energy value of 900 J/m2 could be used, and that the Flexibility Index (FI) value should be set at 20 for heavy-duty asphalt mixes. The SMA12.5-PG76-28 lab-produced asphalt mix was found to be the best performing among the tested mixes.

The results of the life cycle analysis indicated that using SMA12.5-PG76-28 asphalt mix could lead to a significant increase in pavement service life, resulting in cost and material savings in comparison to a currently specified asphalt mix in the York Region. Performance space diagrams were found to be a valuable tool in achieving a balanced mix design and ensuring resistance to both cracking and rutting based on laboratory tests. It was suggested that the HWTT, DC(T), and I-FIT tests, along with current volumetric mix attributes, be used to evaluate the resistance of asphalt mixes to low and intermediate temperature cracking and rutting, in order to produce a durable mix.

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